LOW ENERGY COSMIC RAY INTERACTIONS IN ASTROPHYSICS

Reuven Ramaty
Laboratory for High Energy Astrophysics
Goddard Space Flight Center, Greenbelt, MD 20771, USA

Abstract

Gamma ray emission lines resulting from accelerated particle bombardment of ambient gas can serve as an important spectroscopic tool for abundance determinations. The method is illustrated by considering the gamma ray line emission observed from solar flares. The observation of similar gamma ray lines from Orion suggests the existence of large fluxes of low energy Galactic cosmic rays. The role of these cosmic rays in the nucleosynthesis of the light isotopes is discussed.

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Introduction

The interactions of accelerated particles with ambient matter produce a variety of gamma ray lines following deexcitations in both the nuclei of the ambient medium and the accelerated particles. Astrophysical deexcitation line emission produced by accelerated particle interactions has so far been observed from solar flares[1,2)] and the Orion molecular cloud complex[3)]. Recent general reviews of astrophysical gamma ray line emission are available[4,5)]. The solar gamma ray line observations have many applications, including the determination of solar atmospheric abundances[6,7,8)]. The Orion observations, even though much less detailed, have nonetheless revealed the existence of large fluxes of low energy cosmic rays in this nearest region of recent star formation [e.g. ref.[9)]]. If such cosmic rays are also present at other sites in the Galaxy, then low energy Galactic cosmic rays may play an important role in the nucleosynthesis of the light isotopes ^{6}Li, ^{9}Be, ^{10}B and ^{11}B [refs.[10,11,12)]].

In the present paper we review these topics, referring the reader for more details to the papers referenced above.

Solar Gamma Ray Spectroscopy

The solar flare gamma ray data is now sufficiently detailed to allow the conduct of a meaningful gamma ray spectroscopic analysis of the ambient solar atmosphere. The key is provided by the narrow line emission produced by accelerated protons and α particles interacting with ambient C and heavier nuclei. Owing to their narrower widths, these lines can be distinguished from the broader lines produced by accelerated C and heavier nuclei interacting with ambient H and He. The intensities of the narrow lines depend on the heavy element abundances and thus can be used to determine these abundances. Strong narrow line emission at 4.44, 6.13, 1.63, 1.37, 1.78, and 0.85 MeV, resulting from deexcitations in ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si and ^{56}Fe, respectively, has been observed from many flares. The most recent results, observed with the Solar Maximum Mission (SMM) from 19 flares[2)], allow the

determination[7,8] of the abundance ratios C/O, Mg/O and Mg/Ne for all 19 flares, Si/O for 14 flares and Fe/O for 12 flares.

Unlike atomic spectroscopy, nuclear spectroscopy does not require the temperature and ionic state of the ambient gas, neither of which are always well known. On the other hand, abundance determinations by nuclear spectroscopy do require information on the spectrum of the accelerated particles. For the SMM flare analysis[7,8] the accelerated particle spectra were constrained by using the 1.63 MeV ^{20}Ne-to-6.13 MeV ^{16}O and the 2.22 MeV neutron capture-to-4.44 MeV ^{12}C line fluence ratios, both of which are strong functions of the particle spectrum.

As in other solar atmospheric abundance studies [e.g. ref.[13]], it is useful to distinguish two groups of elements depending on their first ionization potential (FIP): low FIP (<10 eV) elements (Mg, Si and Fe) and high FIP (>11 eV) elements (C, O and Ne). The enhancement of low FIP-to-high FIP element abundance ratios in the corona relative to the photosphere is well established from atomic spectroscopy and solar energetic particle observations [e.g. ref.[13]]. Analysis of the gamma ray data has led to the following conclusions[7,8]:

(i) For the high FIP elements C and O, the derived abundance ratio (by number) is $0.35 \lesssim \mathrm{C/O} \lesssim 0.44$ [Fig. 1, from ref.[8]]. This range is more consistent with C/O = 0.43±0.05 [ref.[14]] than with C/O=0.48±0.1 [ref.[15]]. But taking into account the large uncertainty of the latter, there is no real discrepancy. Furthermore, a single value of C/O is consistent with the data for all 19 flares, implying that C/O could have the same value throughout the gamma ray production region. This is in fact not surprising given that C/O is essentially the same in the photosphere and corona.

(ii) For another pair of high FIP elements, O and Ne, the gamma ray data is in better agreement with Ne/O=0.25 than with the commonly adopted photospheric and coronal value of 0.15. Such a low Ne/O could only be accommodated by a very steep accelerated particle spectrum which would take advantage of the very low threshold for the excitation of the 1.63 MeV level

of ^{20}Ne. The implied particle spectra, however, are too steep to produce sufficient neutrons to account for observations of the 2.22 MeV neutron capture line. In addition, the energy contained in ions with such steep spectra would be inconsistent with the overall flare energetics. Some EUV and X-ray observations[16,17,18] also support a Ne/O higher than 0.15.

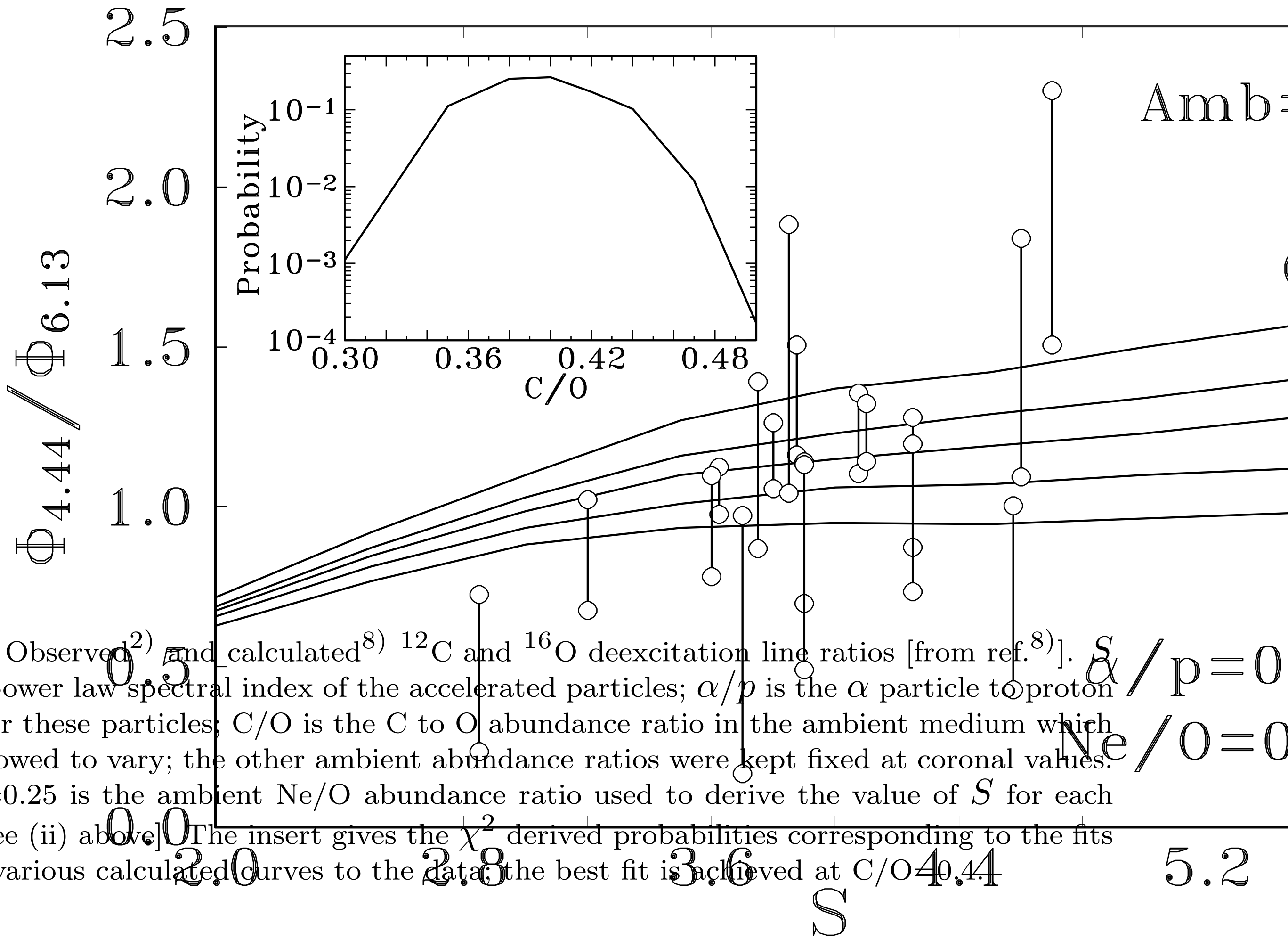

Fig. 1. Observed[2] and calculated[8] ^{12}C and ^{16}O deexcitation line ratios [from ref.[8]]. S is the power law spectral index of the accelerated particles; α/p is the α particle to proton ratio for these particles; C/O is the C to O abundance ratio in the ambient medium which was allowed to vary; the other ambient abundance ratios were kept fixed at coronal values. Ne/O=0.25 is the ambient Ne/O abundance ratio used to derive the value of S for each flare [see (ii) above]. The insert gives the χ^2 derived probabilities corresponding to the fits of the various calculated curves to the data; the best fit is achieved at C/O=0.4.

(iii) To avoid values of Ne/O larger than 0.3 the accelerated particle energy spectra should be at least as steep as an unbroken power law down to about 1 MeV/nucl. For such power laws, the energy contained in the ions for the 19 analyzed flares ranges from about 10^{30} to well over 10^{32} ergs, and is thus comparable or even exceeds the energy contained in the nonrelativistic electrons that produce the hard X-rays in solar flares. Prior to these recent gamma ray analyses, it was widely believed that a large fraction of the released flare energy is contained in nonrelativistic electrons.

(iv) Considering the abundance ratios between elements of different FIP groups [Fig. 2, from ref.[8]], both Mg/O and Mg/Ne show evidence for variability from flare to flare at about the 3σ level. For Mg/O this variation is confined to a range around the coronal value of 0.2 and does not go down to the photospheric value of 0.045. For Si/O and Fe/O the variations are also confined to a range around their respective coronal values. The fact that the low FIP-to-high FIP abundance ratios derived from gamma ray spectroscopy are enhanced relative to their respective photospheric values shows that the gamma ray production region lies above the photosphere.

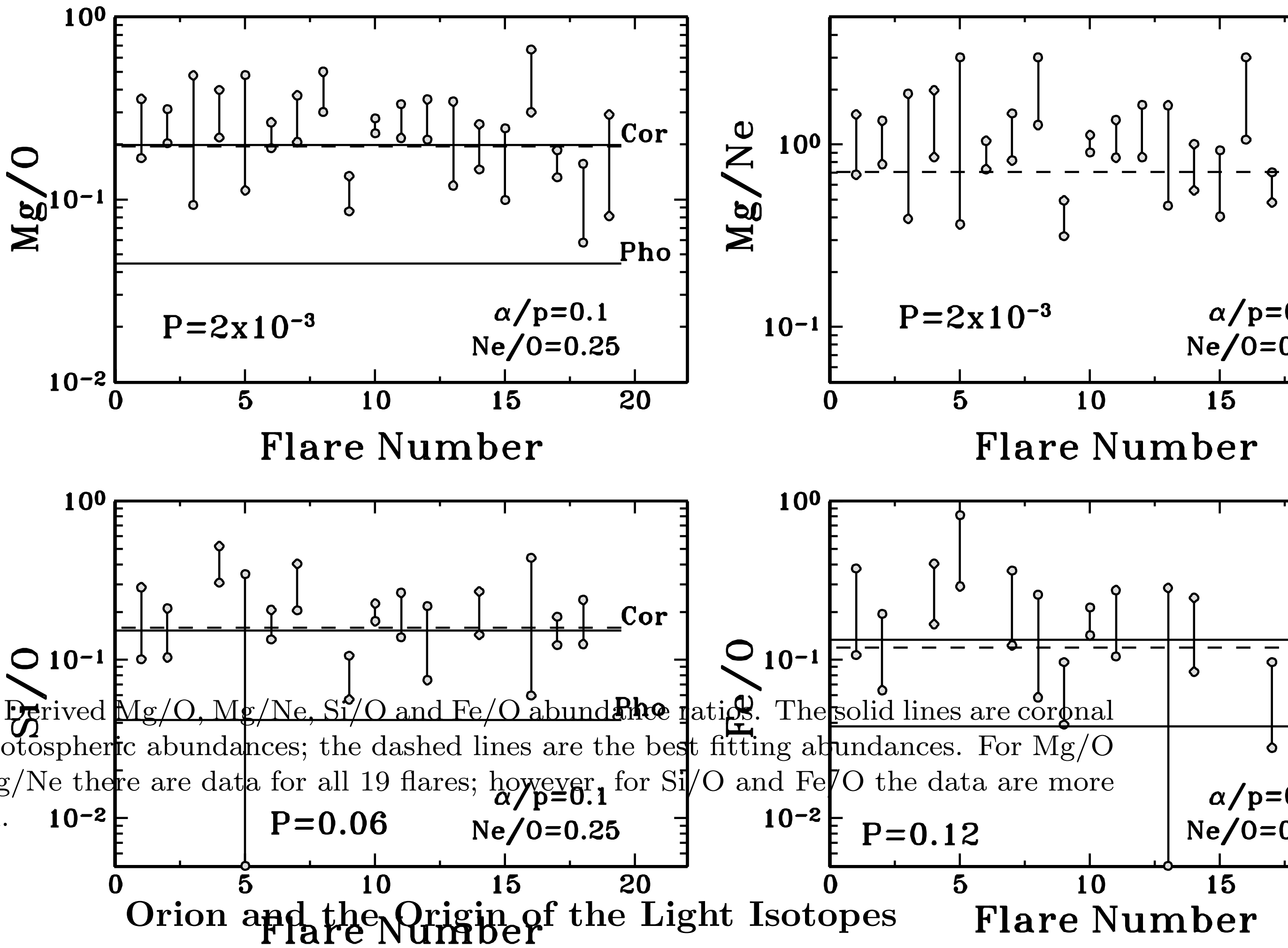

Fig. 2. Derived Mg/O, Mg/Ne, Si/O and Fe/O abundance ratios. The solid lines are coronal and photospheric abundances; the dashed lines are the best fitting abundances. For Mg/O and Mg/Ne there are data for all 19 flares; however, for Si/O and Fe/O the data are more limited.

Orion and the Origin of the Light Isotopes

The discovery[3] of gamma ray line emission from Orion with the COMPTEL instrument on the Compton Gamma Ray Observatory (CGRO) and the implied existence of large fluxes of low energy Galactic cosmic rays, has led to

renewed discussions on the origin of the light elements. Some of the important implications of the Orion gamma ray observations are the following [see ref.[9]) for a more detailed summary):

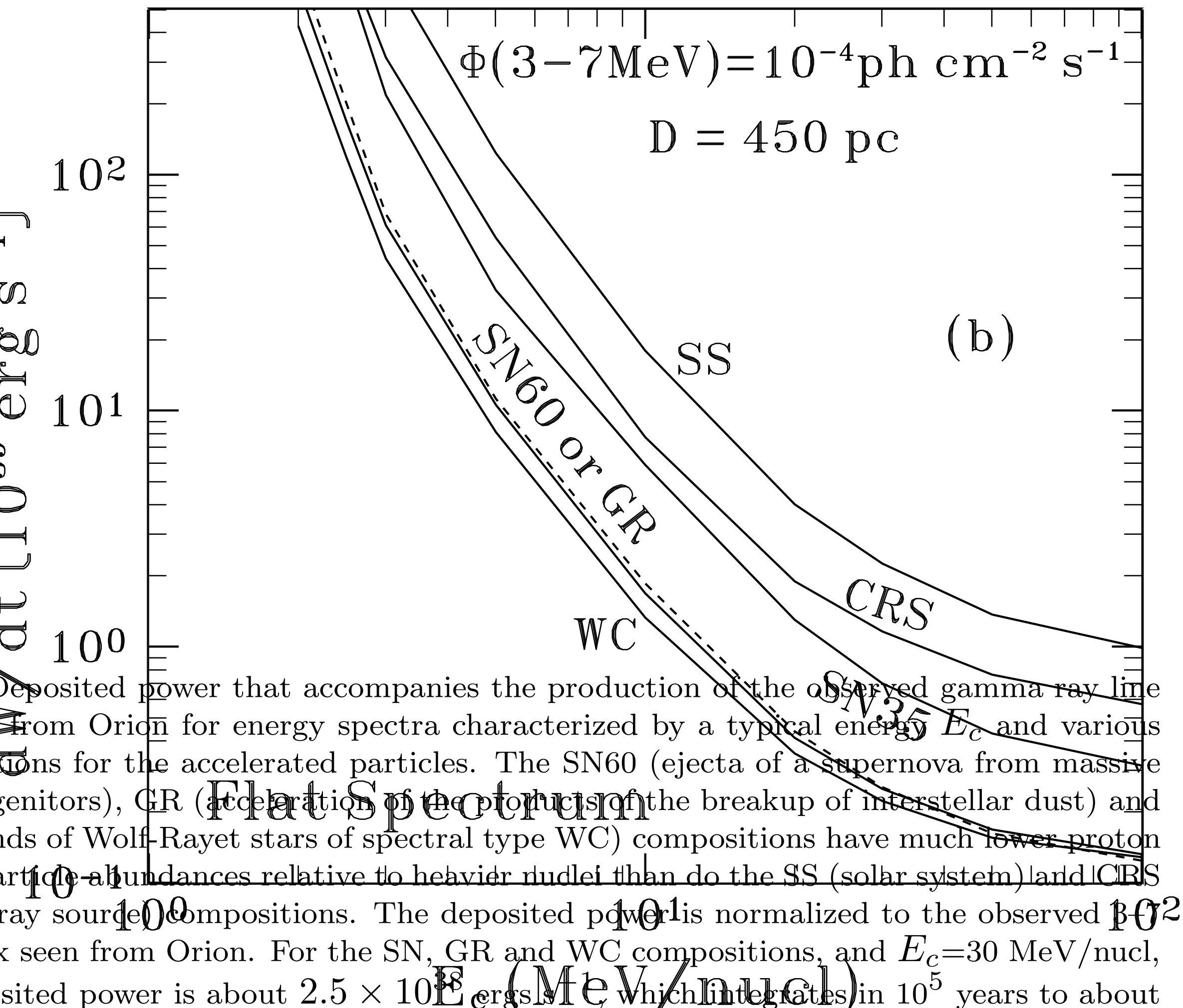

Fig. 3. Deposited power that accompanies the production of the observed gamma ray line emission from Orion for energy spectra characterized by a typical energy E_c and various compositions for the accelerated particles. The SN60 (ejecta of a supernova from massive star progenitors), GR (acceleration of the products of the breakup of interstellar dust) and WC (winds of Wolf-Rayet stars of spectral type WC) compositions have much lower proton and α particle abundances relative to heavier nuclei than do the SS (solar system) and CRS (cosmic ray source) compositions. The deposited power is normalized to the observed 3-7 MeV flux seen from Orion. For the SN, GR and WC compositions, and E_c=30 MeV/nucl, the deposited power is about 2.5×10^{38} ergs s^{-1}, which integrates in 10^5 years to about 7.5×10^{50} ergs in low energy cosmic rays. These cosmic rays could have been accelerated by an 80,000 year old supernova in the OB association whose direction coincides with the centroid of the Orion gamma ray line emission[12]); this supernova is thought[20]) to have produced the Orion-Eridanus bubble seen in soft X-rays. For much lower values of E_c and the other compositions, which are not depleted in protons and α particles, the power required to produce the observed gamma ray line emission is much higher.

(i) The typical energies of the low energy cosmic rays are around tens of MeV/nucleon. For much higher energies gamma ray production via pion decay would lead to gamma ray fluxes which would exceed the observed[19] flux with the EGRET instrument on CGRO. Much lower energies would render the gamma ray line production energetically very inefficient [Fig. 3, from ref.[12])].

(ii) The observed gamma ray line emission is more likely to be produced by accelerated particles which are strongly depleted in protons and α particles relative to heavier nuclei than by particles with a more 'conventional' composition. While in principle this conclusion could follow from the widths of the observed gamma ray lines, in practice the COMPTEL data are still not of high enough quality to allow this distinction[21)]. The conclusion that the proton and α particle abundances are suppressed has come from arguments of energetics: the absence of protons and α particles minimizes the deposited power that accompanies the production of the gamma ray line emission [refs.[11,12)], Fig. 3]. This suppression could be the consequence of the particle injection process prior to the acceleration itself. The proposed injection sources are the winds of Wolf Rayet stars[21)], the ejecta of supernovae from massive star progenitors[10,12)], and the pick up ions resulting from the breakup of interstellar grains[11,12)].

It has been known for over two decades that the relativistic Galactic cosmic rays (GCR) may have produced[22,23)] the observed solar system abundances of ^{6}Li, ^{9}Be and ^{10}B. These cosmic rays, however, cannot account for the abundances of ^{7}Li and ^{11}B. It is believed[24)] that most of the Galactic ^{7}Li is produced in stars and in the Big Bang. Recent measurements[25)] of the boron isotopic ratio in meteorites yielded ^{11}B/^{10}B values in the range 3.84 – 4.25 which exceed the calculated GCR value by a factor of about 1.5. The implications of the Orion gamma ray observations on the origin of the light isotopes have been considered[10,11,12)]. The advantages of producing the light isotopes with 'Orion-like' low energy cosmic rays are the following:

(i) Low energy cosmic rays can produce B such that $^{11}\mathrm{B}/^{10}\mathrm{B} \gtrsim 4$. We illustrate this in Fig. 4 [original to the current paper but based on calculations similar to those presented previously[12)]]. As we have seen, arguments of energetics for Orion favor low energy cosmic rays with E_c around 30 MeV/nucl. At such energies the excess ^{11}B results mostly from ^{12}C via the reactions

^{12}C(p,pn)^{11}C and ^{12}C(p,2p)^{11}B which have lower thresholds than the reaction ^{12}C(p,2pn)^{10}B. At higher energies, and in reactions with ^{16}O, the B isotopic ratio is significantly lower.

(ii) As for the gamma ray production in Orion, if low energy cosmic rays play a role in light element production, then they are probably depleted in protons and α particles. The α particle depletion is necessary in order not to overproduce ^{6}Li; the proton depletion allows a linear dependence of the Be and B abundances on the Fe abundance in stars of various ages. If the low energy cosmic rays are poor in protons and α particles they will produce Be and B only from the breakup of accelerated C and O in interactions with ambient H and He; in this case both the target and projectile abundances could remain constant, leading to a linear growth of the Be and B abundances. On the other hand, the GCR would produce much of the isotopes from the breakup of C and O in the ambient medium whose abundances increase with time, leading to a quadratic growth.

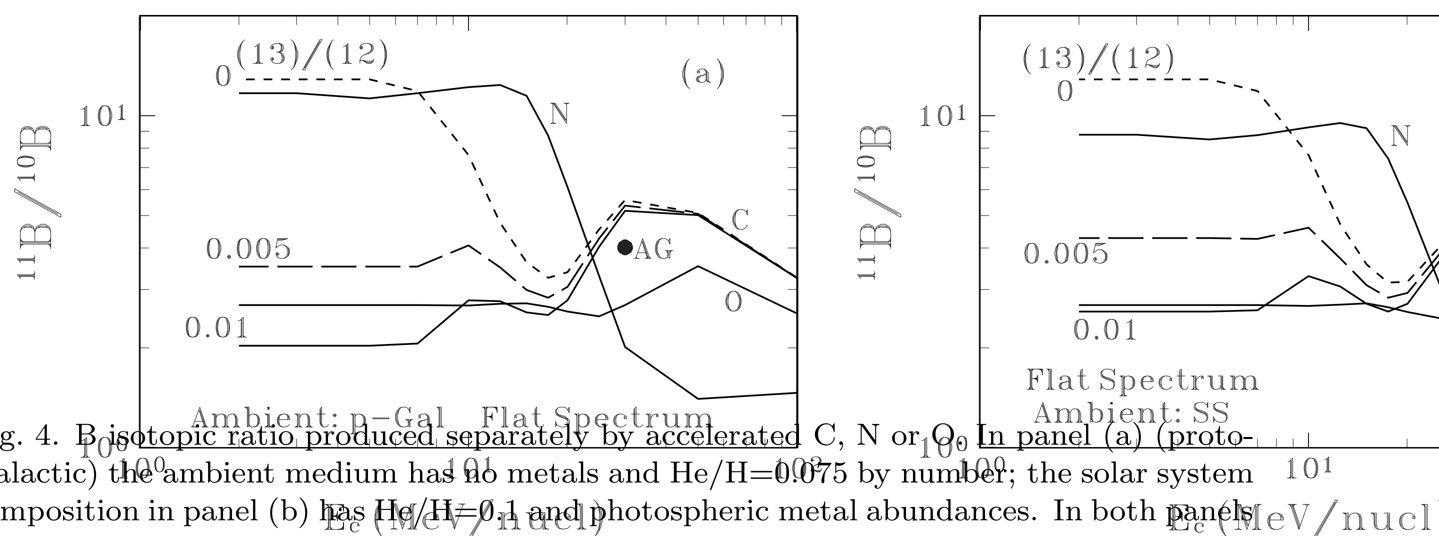

Fig. 4. B isotopic ratio produced separately by accelerated C, N or O. In panel (a) (proto-Galactic) the ambient medium has no metals and He/H=0.075 by number; the solar system composition in panel (b) has He/H=0.1 and photospheric metal abundances. In both panels there are calculations for 3 values for the isotopic ratio of the accelerated C. The AG value is the meteoritic B isotopic ratio[14]. Above about 20 MeV/nucleon the meteoritic ratio requires the presence of C in the accelerated particles.

(iii) The arguments of energetics are also relevant for the light element production. Fig. 5 [from ref.[12]] shows the total energy in accelerated particles that is required to produce 100 M$_\odot$ of B, which is the estimated Galactic inventory of this light element. We see that W increases rapidly as E_c decreases

and that W is minimized by the compositions depleted in protons and α particles. Considering the SN60 case, supernovae from massive star progenitors are excellent candidates for close interaction with molecular clouds since they evolve quite rapidly and thus explode before they have moved very far from the cloud where they were formed. The maximum available energy in low energy cosmic rays from all >60 $M_\odot$ Galactic supernovae is roughly 2×10^{58} ergs, shown as the horizontal bar in Fig. 5. This estimated maximum assumes that all of the Galactic ^{56}Fe of 6×10^7 $M_\odot$ is produced by Type II supernovae from >8 $M_\odot$ progenitors, each producing an average of 0.1 $M_\odot$ of ^{56}Fe. This gives a total of 6×10^8 Type II supernovae in the age of the Galaxy. Scaling of the supernova rate by an initial mass function proportional to $M^{-2.7}$, then gives a maximum of 2×10^7 Type II supernovae from $>60M_\odot$ progenitors, each of which could have as much as $\sim 10^{51}$ erg of mechanical energy available for low energy cosmic ray acceleration. This energetic argument thus gives further support to the previous conclusions that the light elements are produced by low energy cosmic rays of typical energies around 30 MeV/nucl and depleted in protons and α particles.

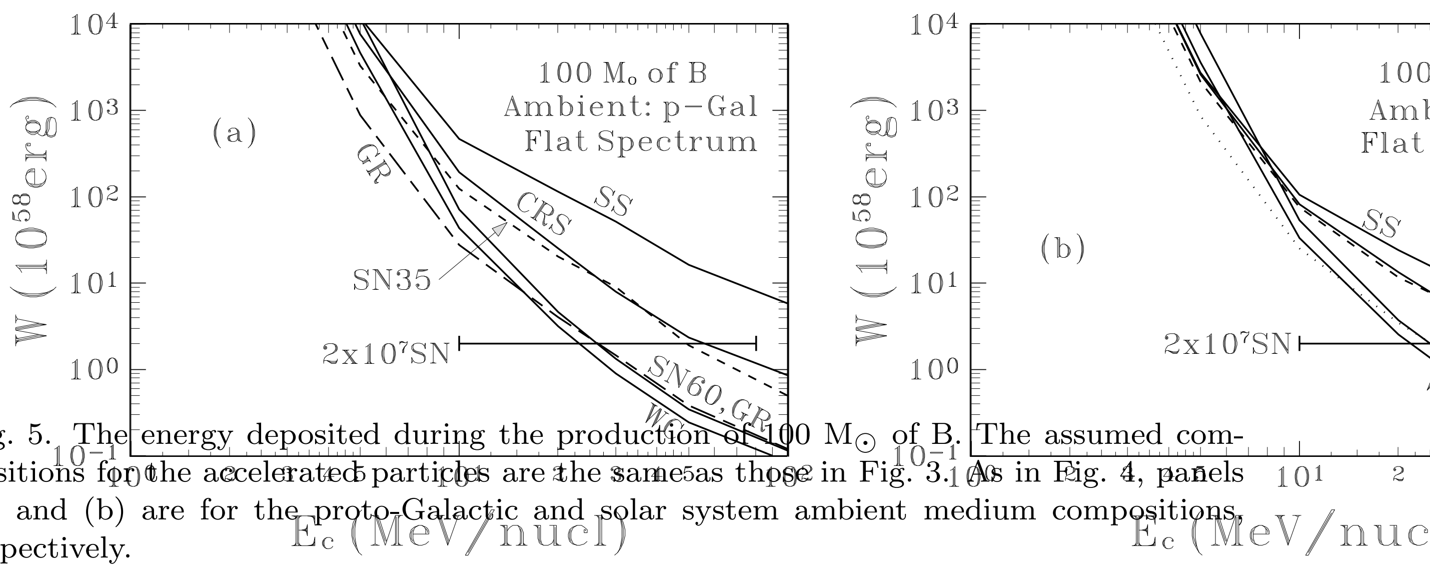

Fig. 5. The energy deposited during the production of 100 $M_\odot$ of B. The assumed compositions for the accelerated particles are the same as those in Fig. 3. As in Fig. 4, panels (a) and (b) are for the proto-Galactic and solar system ambient medium compositions, respectively.

Summary

We have used solar flare observations to demonstrate the new technique of abundance determination based on gamma ray line emission produced by

accelerated particle bombardment. We have also reviewed some of the implications of similar gamma ray line emission observed from Orion, including the production of light elements by low energy cosmic rays.

For such an origin for the light elements, limitations on the total available energy in low energy cosmic rays imply that the production takes place at relatively high particle energies, around 30 MeV/nucl. Such low energy cosmic rays can reproduce the meteoritic B isotopic ratio of 4, but they require an accelerated C/O on the order of the observed solar system ratio ($\sim$0.5). If in the early Galaxy C/O in the ejecta of Type II supernovae from massive star progenitors (which are thought to be the sources of the postulated cosmic rays) is much lower, then the B isotopic ratio in low metallicity stars should be significantly lower than the measured meteoritic value.

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